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A Two-Stage Procedure Toward the Efficient Implementation of PANS and Other Hybrid Turbulence Models

Khaled S. Abdol-Hamid
Langley Research Center, Hampton, Virginia

Sharath S. Girimaji
Texas A&M University, College Station, Texas

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

The main objective of this article is to introduce and to show the implementation of a novel two-stage procedure to efficiently estimate the level of scale resolution possible for a given flow on a given grid for Partial Averaged Navier-Stokes (PANS) and other hybrid models. It has been found that the prescribed scale resolution can play a major role in obtaining accurate flow solutions. The first step is to solve the unsteady or steady Reynolds Averaged Navier-Stokes (URANS/RANS) equations. From this preprocessing step, the turbulence length-scale field is obtained. This is then used to compute the characteristic length-scale ratio between the turbulence scale and the grid spacing. Based on this ratio, we can assess the finest scale resolution that a given grid for a given flow can support. Along with other additional criteria, we are able to analytically identify the appropriate hybrid solver resolution for different regions of the flow. This procedure removes the grid dependency issue that affects the results produced by different hybrid procedures in solving unsteady flows. The formulation, implementation methodology, and validation example are presented. We implemented this capability in a production Computational Fluid Dynamics (CFD) code, PAB3D, for the simulation of unsteady flows.

Introduction

The limited capability of the Reynolds Averaged Navier-Stokes (RANS) approach combined with eddy-viscosity turbulence models to simulate unsteady and complex flows has been well known for some time. The RANS' assumption is that most of the energy is modeled through the turbulence transport equations and is resolved in the grid. RANS also overpredicts the eddy viscosity, which results in excessive damping of unsteady motion. Consequently, the eddy viscosity attains unphysically large values due to unresolved scales, and suppresses most temporal and spatial fluctuations in the resolved flow field. One of the approaches used to overcome this problem is to provide a mechanism for the RANS equations to resolve the largest scales of motion. Among several methods, the Detached Eddy Simulations (DES) [1], the hybrid Large Eddy Simulation (LES) [2-3], the Limited Numerical Scheme (LNS) [4] and the Partial Averaged Navier-Stokes (PANS) [5] provide the mechanism best needed to satisfy this requirement.

PAB3D is a structured, multiblock, parallel, implicit, finite-volume solver of the three-dimensional RANS equations. Investigations in the area of unsteady flow control for propulsion applications have led to an increased interest in upgrading PAB3D's [6-8] time-accurate capabilities. Advanced turbulence models are available in the code, which are widely used in internal and external flow applications by NASA and by the US aerospace industry.

In an attempt to increase the fidelity and accuracy of the PAB3D code, a hybrid turbulence model RANS/LES [2-3] has been added. Another new feature to PAB3D is the addition of the PANS method, which was suggested by Girimaji [4]. The PANS model was developed to overcome the grid dependency associated with the use of the hybrid RANS/LES models. The primary objective of this paper is to develop a procedure which can help in the efficient implementation of PANS and other hybrid methods.

We implemented this capability in a production Computational Fluid Dynamics (CFD) code, PAB3D, for the simulation of unsteady flows. The formulation, implementation methodology, and validation example are presented in support of the enhanced PAB3D's time-accurate and turbulence modeling capabilities. The new features were utilized to compute the flow field past a stationary cylinder at Re=50,000. We provide three-dimensional RANS and PANS simulations for this flow. Predictions of the Strouhal number St, the drag coefficient C_D, and the lift coefficient C_L are presented. We will only consider the case in which the flow at the separation point is laminar. This preliminary result opens the way to the potential capability of PANS in simulating the unsteady flow phenomena for complex aerodynamic configurations.

The organization of the paper will be as follows:

1) The governing equations of the RANS and PANS formulations will be presented and discussed in detail, and

2) Computational results from RANS and PANS for a flow past a stationary cylinder will be presented, examined, and compared to experimental data. Flow around a cylinder is considered as a standard test case for the hybrid turbulence model [9-11], because it poses a basic flow physics problem and is inherently unsteady.

Approaches

The governing equations of the time-averaged formulation include the conservation equations for mass, momentum, and energy, and the equation of state. In the present study, the perfect gas law is chosen to represent the air properties, and the eddy-viscosity concept is used to model the Reynolds stresses. The mass, momentum, and energy conservation equations of the time-averaged equations can be written in a conservative form as follows:

$$
\begin{aligned}
&\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \\
&\frac{\partial \rho u_i}{\partial t} + \frac{\partial(\rho u_i u_j + p\delta_{ij})}{\partial x_j} = \frac{\partial(\tau_{ij} - \rho \overline{u_i u_j})}{\partial x_j} \\
&\frac{\partial \rho e_0}{\partial t} + \frac{\partial(\rho e_0 u_i + p u_i)}{\partial x_i} = \frac{\partial(\tau_{ij} u_j - \rho \overline{u_i u_j} u_j)}{\partial x_i} - \frac{\partial(q_i + C_P \rho\, \overline{u_i \theta})}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu_l + \frac{\mu_t}{\overline{\sigma}_k}\frac{\partial k}{\partial x_i}\right]
\end{aligned}
\tag{1}
$$

In the case of Reynolds Averaged Navier-Stokes (RANS) equations, a Standard Turbulence Model (STM) such as the two-equation (kε) turbulence model is used:

$$
\begin{aligned}
&\frac{\partial \rho k}{\partial t} + \frac{\partial \rho u_j k}{\partial x_j} = -\rho \overline{u_j u_i}\frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu_l + \frac{c_\mu k^2}{\overline{\sigma}_k \varepsilon}\frac{\partial k}{\partial x_j}\right] - \rho\varepsilon(1. + M_\tau^2) \\
&\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial \rho u_j \varepsilon}{\partial x_j} = -C_{\varepsilon 1}\rho \overline{u_j u_i}\frac{\partial u_i}{\partial x_j}\frac{\varepsilon}{k} + \frac{\partial}{\partial x_j}\left[\mu_l + \frac{c_\mu k^2}{\overline{\sigma}_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] - f_2 \tilde{C}_{\varepsilon 2}\rho\frac{\varepsilon}{k}\left[\varepsilon - \nu_l\left(\frac{\partial\sqrt{k}}{\partial n}\right)^2\right]
\end{aligned}
\tag{2}
$$

$$C_\mu = .09, C_{\varepsilon 1} = 1.44,$$
$$\overline{\sigma}_k = \sigma_k = 1.4, \overline{\sigma}_\varepsilon = \sigma_\varepsilon = 1 \ and \ \overline{C_{\varepsilon 2}} = C_{\varepsilon 2} = 1.92$$

$$f_\mu = \exp\left[\frac{-3.41}{\left(1+\frac{R_T}{50}\right)^2}\right], \ R_T = \frac{k^2}{\mu_t \varepsilon}, f_2 = 1. - 0.3\exp\left(-R_T^2\right)$$

The boundary conditions for ε and k at the wall are:

$$\varepsilon_{wall} = \nu_l \left(\frac{\partial\sqrt{k}}{\partial n}\right)^2$$

$k_{wall} = 0.$

The turbulent stress components are formulated as:

$$\rho\overline{u_j u_i} = \quad 2\rho\upsilon_t S_{ji} - \frac{2}{3}\delta_{ji}\rho k$$

$$S_{ji} = \frac{1}{2}\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right] - \frac{1}{3}\delta_{ji}\frac{\partial u_j}{\partial x_i} \qquad (3)$$

For the purpose of this paper, we will define RANS turbulent viscosity as

$$\upsilon_t^{RANS} = f_\mu \rho C_\mu \frac{k^2}{\varepsilon} \qquad (4)$$

The PANS model [5] was developed to overcome the grid dependency associated with the use of other Hybrid Turbulence Models (HTM). In its original form, PANS [5] replaces the two-equation turbulence model by solving for the unresolved kinetic energy k_u and the dissipation ε_u. The k_u equation is identical to the original k equation. In the ε equation, the following coefficients are used to change the two-equation model to the Hybrid Turbulence Model (HTM), which becomes known as the PANS formulation through the following changes:

$$\begin{aligned} \tilde{C}_{\varepsilon 2} &= f_k\left(C_{\varepsilon 2} - C_{\varepsilon 1}\right) + C_{\varepsilon 1} \\ \overline{\sigma}_k &= f_k^2 \sigma_k \ and \ \overline{\sigma}_\varepsilon = f_k^2 \sigma_\varepsilon \end{aligned} \qquad (5)$$

The original formulation uses a constant value for the unresolved kinetic energy parameter (f_k). The users will select a value for this parameter and refine the grid until the flow solution converges toward a solution target. This could be very time consuming for resolving complex three-dimensional flows.

Single-Stage Approach (PANS-v1)

Elmiligui et al. [12] introduced an attempt to use a variable f_k with time and space instead of using the constant value. In reference 12, the following equation is used to compute f_k as:

$$f_k = \{1. + \tanh[2\pi(\Lambda - 0.5)]\}/2. \qquad (6)$$

In this case, turbulent length scale is defined as:

$$l_u = k_u^{2/3}/\varepsilon_u, \ \Lambda = \frac{1}{1+\lambda^{4/3}},$$

and the characteristic length scale ration as :

$$\lambda = \frac{l_u}{\Delta}, \ \Delta = \max(\Delta_x, \Delta_y, \Delta_z)$$

Δ_x, Δ_y, and Δ_z are the grid cell distances in the x, y, and z directions, respectively. The function in equation (6) has the characteristic to be equal to 1.0 in the viscous sub-layer, as the unresolved characteristic ratio tends to be of very small value. Also, the value of this function is restricted to 1, in case the RANS turbulent viscosity becomes smaller than the LES viscosity. We define LES viscosity as:

$$\upsilon_t^{LES} = 0.084\Delta\sqrt{k^{LES}} \ \text{and} \ k^{LES} = f_k k \quad (7)$$

Two-Stage Approach

Some of the drawbacks of such a function used in PANS-v1 are that it varies with time and space and that it could be affected by grid resolution. In this section, we use another approach to construct a function which varies only with space.

One of the major deficiencies associated with the heretofore published use of hybrid schemes such as DES and PANS is that there is no clear identification of the different flow regions as shown in Figure 1. These regions need to be clearly defined as RANS regions and DES/PANS regions in order to achieve complete simulation, independent of grid resolution. Several researchers [2, 3, 12, 13 and 14] observed that in most cases, using hybrid methods, the use of fine grid might result in incorrect simulations. We believe that this is caused by the fact that the DES/PANS regions encroach into the RANS regions and destroy the ability of the hybrid methods to produce correct simulation. It should be understood that hybrid methods rely on the RANS regions in order to correctly develop the other flow regions.

It is quite difficult to develop a method that isolates the RANS regions at all times within a hybrid simulation. One approach is to pre-design the grid as done by Travin et al. [13] in the case of the flow around a stationary cylinder. This can be accomplished for a very simple flow, where we can easily identify the different flow regions. In the present paper, we introduce a more general approach to define these flow regions. This approach uses a two-stage procedure to define f_k. In the first stage, we solve the problem using Standard Turbulence Models (STM) such as a linear two-equation model. We use the results of this simulation to identify the regions where grid resolution is high enough to allow for hybrid simulation such as PANS. Also, we extract information about which regions of the flow we must set to $f_k = 1.0$ in order to maintain a RANS simulation. We have come to the decision that the most appropriate parameter for assessing the grid resolution is the characteristic turbulence length-scale ratio.

Here, we will highlight the basic concepts of this approach. Based on a simple dimension analysis, we assume that the turbulent viscosity may be related to the total kinetic energy (k),ε, S and Δ as:

$$\upsilon_t \approx \frac{k_u^{\,2}}{\varepsilon} \approx \Delta^2 S \approx \Delta^2 \frac{\varepsilon}{k_u} \qquad (8)$$

$$\varepsilon = \frac{k^{3/2}}{L_T}$$

$$k_u = f_k k$$

L_T is the characteristic turbulence length scale, which leads to

$$f_k^3 k^3 \approx \Delta^2 \frac{k^3}{L_T^2} \quad (9)$$

$$\lambda = \frac{L_T}{\Delta}$$

Hence,

$$f_k = C_h \left[\frac{1}{\lambda}\right]^{2/3} \quad (10)$$

C_h is a model coefficient of order one, which needs to be calibrated. In the present paper, we will use a value of one to evaluate the model. We will introduce two forms of the two-stage approach. First is the sequential form, which can be applied to wide range of unsteady flow conditions. We have successfully implemented and tested this form in the PAB3D CFD code. The second form is more complicated and requires major changes in CFD codes and needs larger resources. However, this second form offers a greater potential for solving more complicated flow problems such as moving bodies.

A. Sequential Two-Stage Approach (PANS-v2)

The simplest form of the two-stage procedure is shown in Figure 2a. The users will need to solve either the time-accurate or steady state RANS equations depending on the flow conditions. In the case of unsteady flow simulation, it is necessary to compute the time-average of the characteristic length-scale ratio. Equation (10) is then used to calculate f_k. During the second stage (the hybrid method phase), this value will be fixed in time but it will vary in space. The users can quickly find out if the grid resolution is appropriate to carry out the PANS or other hybrid simulations. The second stage of this procedure is not in any way limited to use with PANS. In fact, any of the hybrid methods could use the results of the first stage to construct a primary filter for use with these methods. This filter can be used to identify and isolate the RANS regions during the second stage of the simulation. In the present paper, we use the two-equation model described in the previous section to provide the first-stage solution. We refer to this procedure as PANS-v2.

Here, we summarize the guidelines to be followed for the sequential two-stage procedure. These guidelines are completely dependent upon flow complexity. For the first stage:

1. Complete a three-dimensional, or two-dimensional simulation
2. Unsteady or steady calculation, high-order schemes are not required
3. Desired level of an allowable RANS turbulence model (one-equation, two-equation, Algebraic Stress, full Reynolds Stress, …etc.)

For the second stage:

1. Three-dimensional simulation
2. Unsteady calculation, high-order schemes should be considered
3. Hybrid models used (DES, Hybrid RANS/LES, PANS, …etc.)

The users need to use the same flow conditions, boundary conditions, and grid resolution for both stages of the procedure.

B. Concurrent Two-Stage Approach (PANS-v3)

The concurrent form of the two-stage procedure is shown in Figure 2b. Users will need to solve RANS with standard turbulence model (STM) equations and time-averaged equations such as PANS with hybrid turbulence model (HTM) equations simultaneously during code execution. From the first-stage, we extract the instantaneous characteristic length-scale ratio and produce f_k. During the second-stage (the hybrid method phase), this value will be used with the selected HTM to close the PANS equations. This process is repeated for each time step of the flow simulation. This approach is not demonstrated herein.

Results and Discussions

Flow past a stationary cylinder was computed at a Re =50,000 to validate the implementation of an efficient two-stage procedure for solving hybrid turbulence models. The grid consisted of 1,290,240 cells and 24 blocks, extended 15 diameters into the far field in the radial directions, and covered a two-cylinder diameter in the span-wise direction. This grid was developed and used by Vatsa et al. [14]. The same grid was used for all runs, which gave a first grid height $y+$ range of approximately .2 to 2.0 around the cylindrical surface. A non-dimensional time step of 0.015 (based on free stream speed and the diameter of the cylinder) was used. Based on the time step, approximately 350 frames of solutions in time per cycle of shedding were sampled. Four sub-iterations per time-step were used to reduce the error. The cases each required approximately 48 hours of CPU, using 24 (2.8 GHz P4) computers.

The Laminar Separated (LS) case was chosen to evaluate the implementation of the PANS formulations into PAB3D code, and to investigate their capability to simulate such flow. References 12,13 and 14 each gave a complete description of this case and the different computational procedures. This case is compared with the experimental data of Cantwell and Coles [15]. We followed the procedure as described in Figure 2a. First, we used the RANS formulation to get time-averaged quantities to calculate the characteristic length-scale ratio (λ as shown in figure 3a). This ratio varies in space and is used to produce the unresolved kinetic energy parameter (f_k). Figure 3b shows the distribution of this function at a selected spanwise (y) location. This parameter identifies the RANS and PANS regions. The RANS regions are defined with the parameter set at a value of one. The PANS regions are, for all the values, less than one. We use this parameter in solving the PANS formulation. Figure 4 shows the unresolved turbulent kinetic energy produced with the use of RANS (4a) and PANS (4b) formulations. The results of the RANS simulation were ten times those produced by the PANS formulation. More energy was resolved using the PANS formulation as compared with that resolved by the URANS simulations.

Figure 5 shows the power spectral density (PSD) as a function of the Strouhal number, St, from RANS and PANS results. It is clear that RANS produced a peak PSD level at only one major Strouhal number and no significant minor ones. This result indicates that the 3D RANS simulation has a two-dimensional flow character. The vorticity plot shown in Figure 6 supports this conclusion as it shows the carpet-like flow with no change in the Y-direction. On the other hand, the PANS result shows PSD peaks at one major Strouhal number and several minor peaks at other St values, indicating that more scales were resolved in this simulation. Figure 7 shows the three-dimensional character of the flow produced as a result of the PANS formulation.

The time-averaged surface pressure distributions from the 3-D simulations are compared with the experimental data of Cantwell and Coles [15] in Figure 8. Table 1 shows the comparison between the recent PAB3D simulations, the DES solutions of Travin et al. [13], and the experimental data. The present PANS formulations produced results comparable to the DES Travin et al. [13], and experimental data.

Table 1. Re=50,000 LS Time-Averaged Results

Method	C_D	$-C_{pb}$	St
3D-DES Travin et al. [13]	1.27	1.28	0.21
2D-DES Travin et al. [13]	1.77	2.05	0.14/0.2
3D PAB3D PANS-v1	1.1	1.03	0.21
3D PAB3D PABS-v2	1.14	1.18	0.21
2D/3D PAB3D RANS	1.08	1.03	0.23
Experiment	1.25	1.2	0.18-0.21

Summary and Future Work

We have introduced and implemented a novel two-stage procedure to efficiently estimate the level of scale resolution possible for a given flow on a given grid for Partial Averaged Navier-Stokes (PANS) and other hybrid models. The new capabilities improve the accuracy and robustness of creating a simulation of an unsteady flow field. In this paper, a new approach to prescribe the f_k function was presented. This is a two-stage procedure, which is designed to remove the grid dependency of the hybrid RANS models. In the first-stage, we use the RANS simulation with a Standard Turbulence Model (STM) such as $k\varepsilon$ to produce an estimate of f_k over the entire grid domain. In the second-stage, we supply f_k for the selective application of a Hybrid Turbulence Model (HTM) such as PANS formulation in regions where the grid density is sufficient to resolve a portion or all of the large-scale flow structures. In the present implementation, f_k is a function of length-scale and grid size, which represent a characteristic length-scale ratio. For the simple two-stage approach, this function only varies with space throughout an unsteady flow simulation.

In this technical memorandum, we selected the Laminar Separated (LS) case to examine the capability of the PANS formulation. With the use of the simple two-stage procedure an improved prediction capability is achieved in predicting C_D, St, and the surface pressure distribution when compared to experimental data. This implementation is a first step towards adding a variable resolution turbulence model capability to CFD codes. We can now use the PAB3D code to refine the PANS formulation and to conduct validation computations using a variety of simple and complex flow physics problems.

The present procedure represents the first step in the development and implementation of a more comprehensive approach for solving unsteady flows. This approach needs to be calibrated, verified and validated for a wide range of flow problems such as jet, cavity and others. Flows with moving bodies will present a great challenge for the present approach. This challenge could be addressed by extending the present procedure to the concurrent two-stage form. The concurrent two-stage procedure will require solving RANS with Standard Turbulence Model and time-averaged equations such as PANS with Hybrid Turbulence Model simultaneously at each time step for a total of 14 equations. This approach will need large resources of computers and code development for successful implementation.

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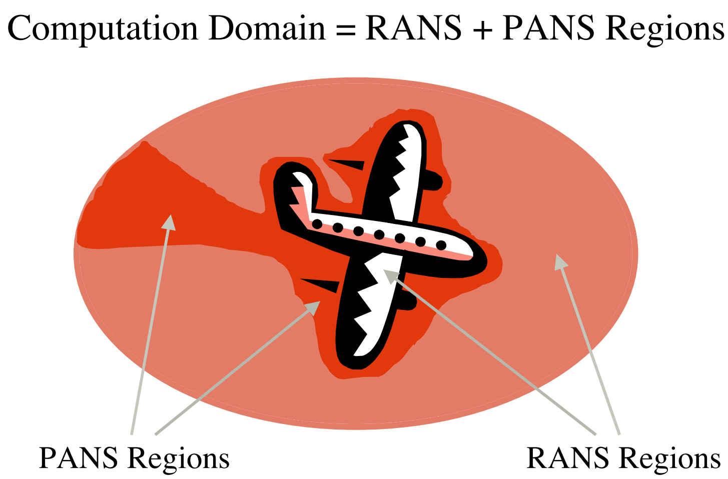

Figure 1. Regions for the use of PANS and RANS

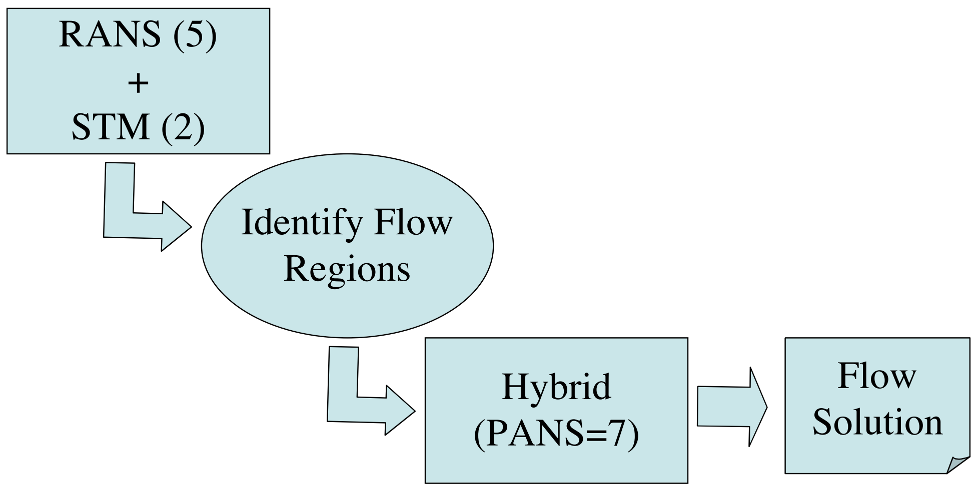

Figure 2a. Sequential Two-Stage Procedure for Solving Hybrid Turbulence Models

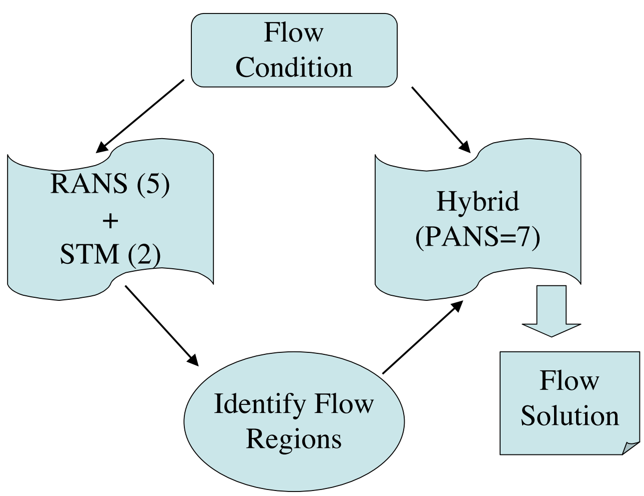

Figure 2b. Concurrent Two-Stage Procedure for Solving Hybrid Turbulence Models

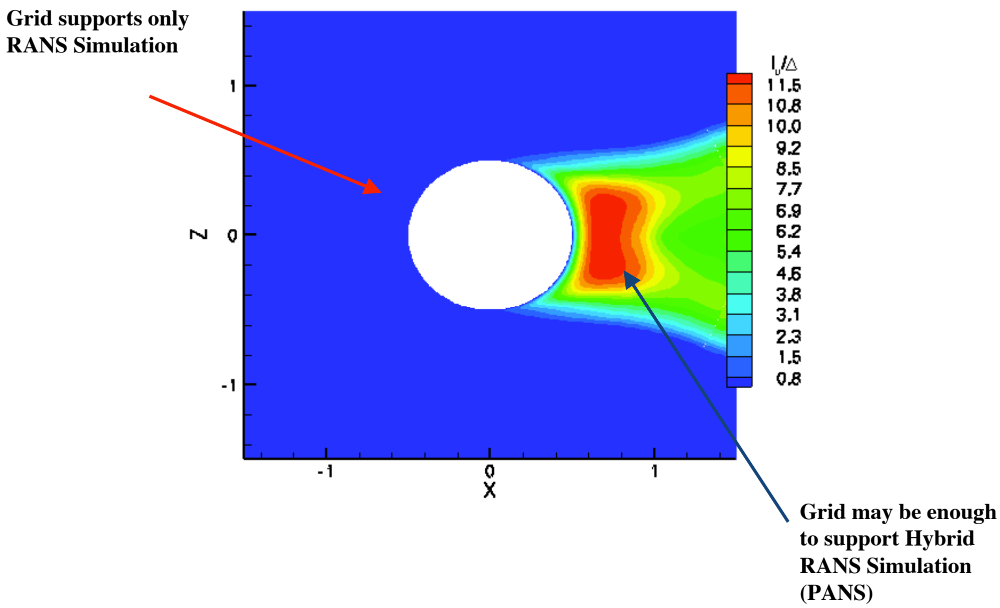

Figure 3a. Characteristic Length-Scale Ratio (λ), Contours at Y=1.0 produced from RANS Simulation (Re=50,000)

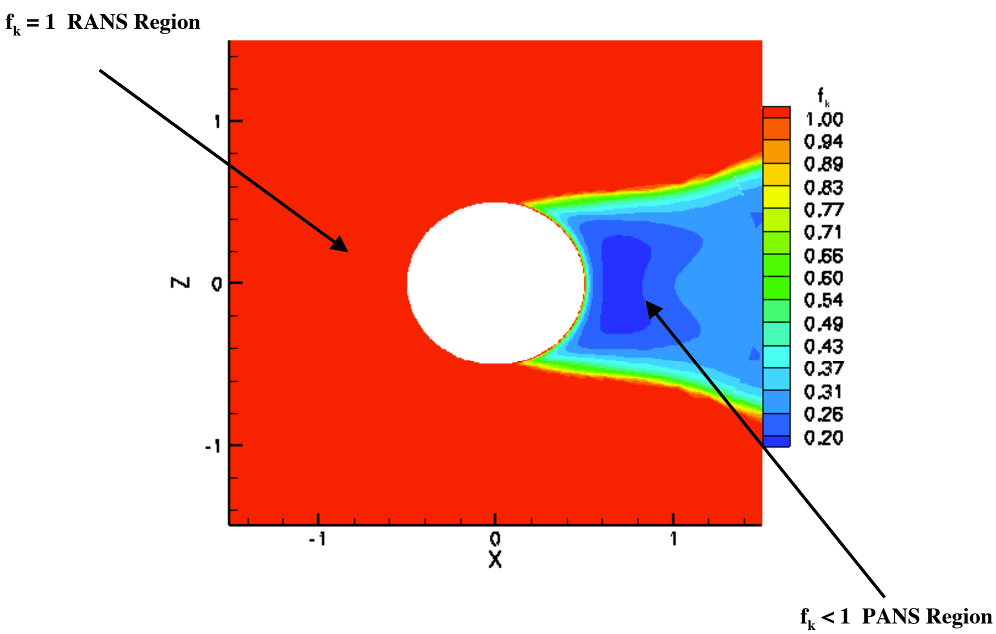

Figure 3b. Unresolved Turbulent Kinetic Energy Parameter, f_k Contours at Y=1.0 Produced from RANS Simulation (Re=50,000)

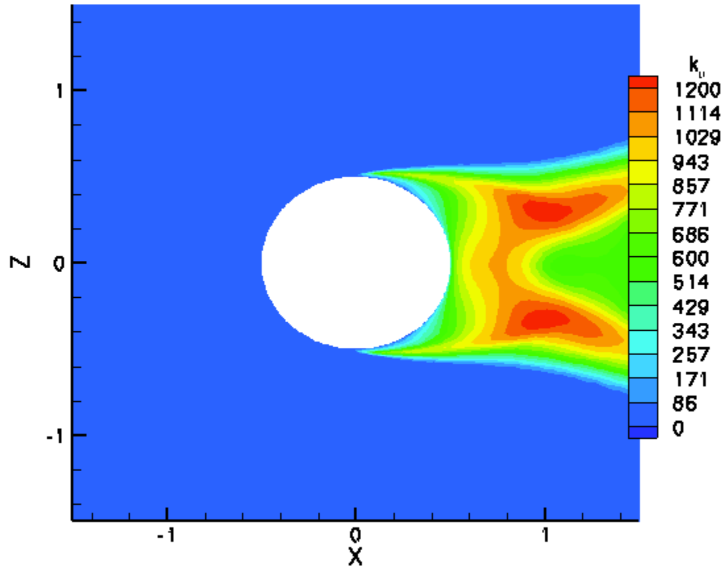

Figure 4a. Unresolved Turbulent Kinetic Energy, k_u (m^2/sec^2), Contours at Y=1.0 Produced from RANS Simulation (Re=50,000)

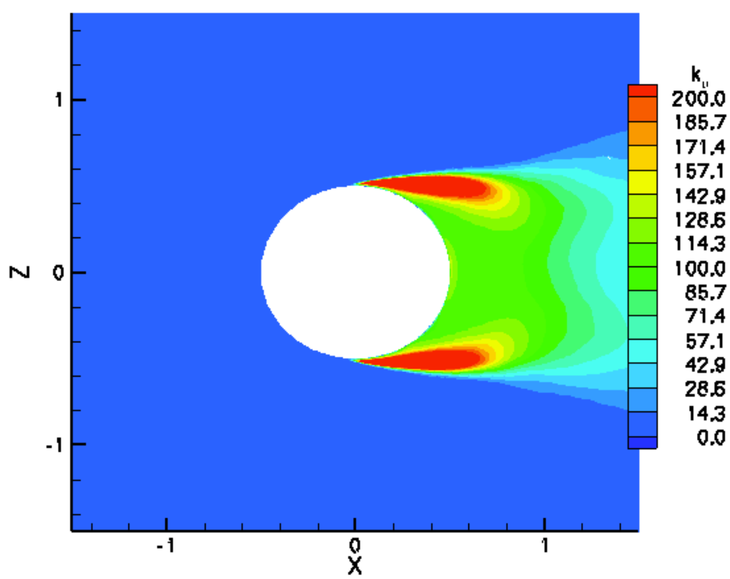

Figure 4b. Unresolved Turbulent Kinetic Energy, k_u (m^2/sec^2), Contours at Y=1.0 Produced from PANS-v1/v2 Simulation (Re=50,000)

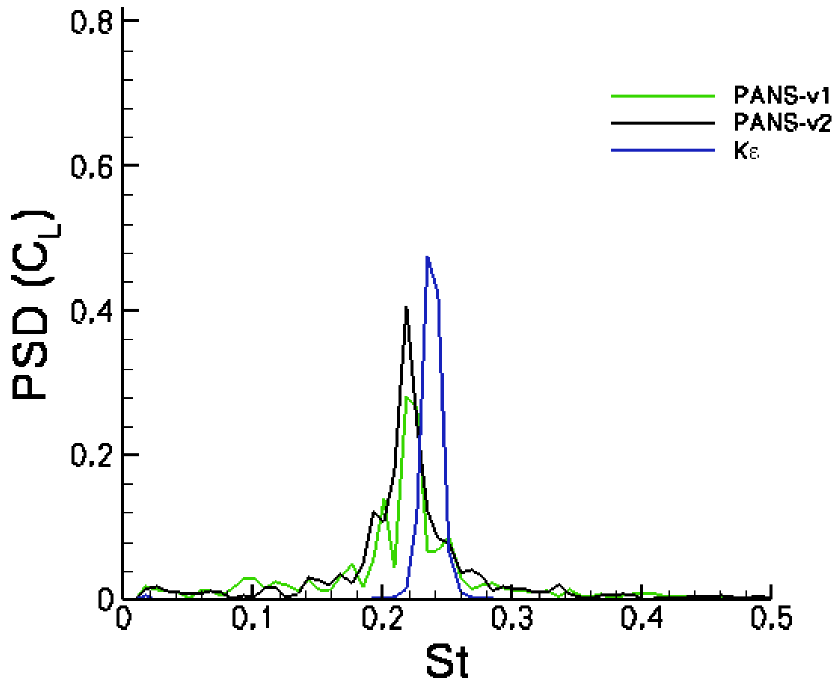

Figure 5. Power Spectral Density vs Strouhal Number Results from kε RANS and PANS Formulations (Re=50,000).

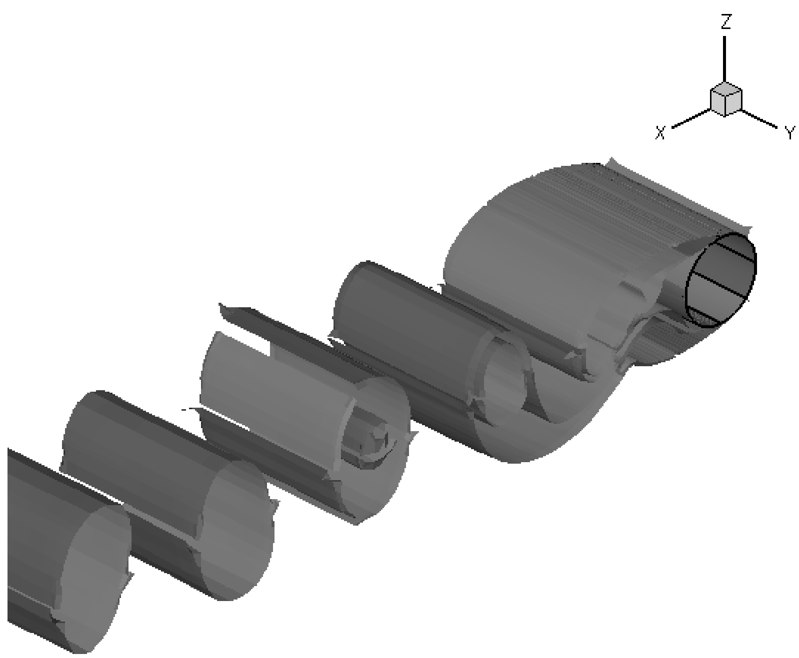

Figure 6. Three-Dimensional Vorticity Magnitude Results from RANS Simulation (Re=50,000)

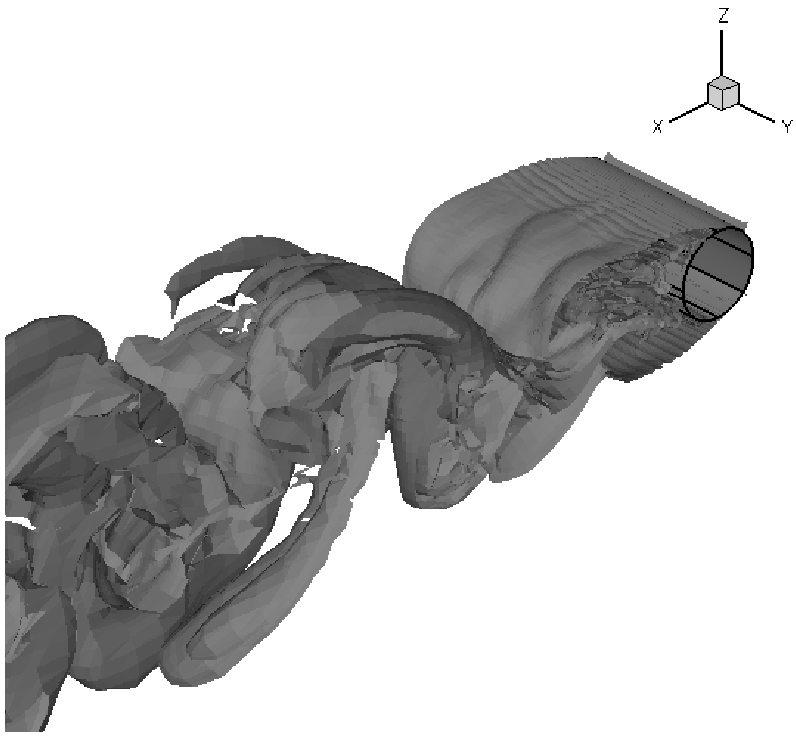

Figure 7. Three-Dimensional Vorticity Magnitude Results from PANS Formulation (Re=50,000).

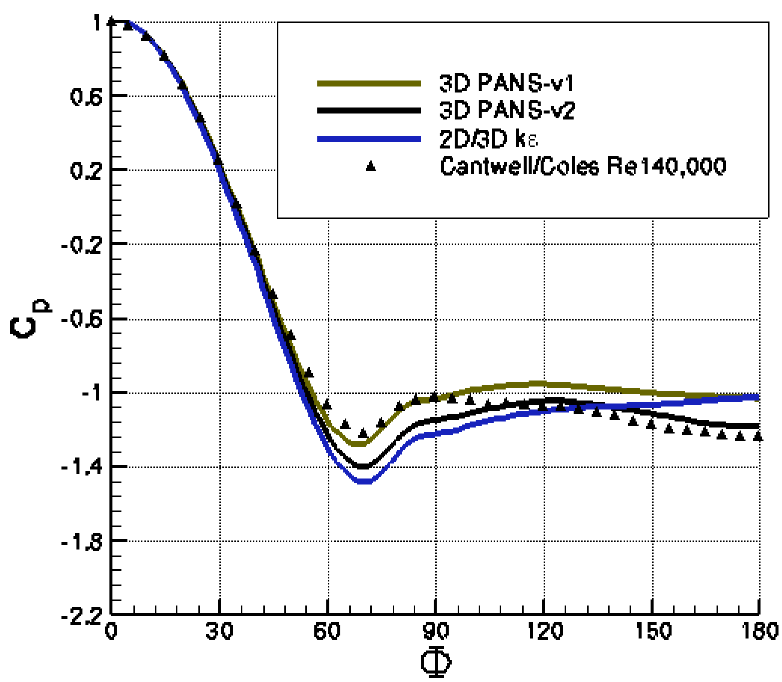

Figure 8. Coefficient of Pressure on the Cylinder Surface using kε RANS and PANS formulations Compared with Experimental Data

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14. ABSTRACT
The main objective of this article is to introduce and to show the implementation of a novel two-stage procedure to efficiently estimate the level of scale resolution possible for a given flow on a given grid for Partial Averaged Navier-Stokes (PANS) and other hybrid models. It has been found that the prescribed scale resolution can play a major role in obtaining accurate flow solutions. The first step is to solve the unsteady or steady Reynolds Averaged Navier-Stokes (URANS/RANS) equations. From this preprocessing step, the turbulence length-scale field is obtained. This is then used to compute the characteristic length-scale ratio between the turbulence scale and the grid spacing. Based on this ratio, we can assess the finest scale resolution that a given grid for a given flow can support. Along with other additional criteria, we are able to analytically identify the appropriate hybrid solver resolution for different regions of the flow. This procedure removes the grid dependency issue that affects the results produced by different hybrid procedures in solving unsteady flows. The formulation, implementation methodology, and validation example are presented. We implemented this capability in a production Computational Fluid Dynamics (CFD) code, PAB3D, for the simulation of unsteady flows.

15. SUBJECT TERMS
Turbulence Models; Reynolds Averaged Navier-Stokes (RANS) equations; Partial Averaged Navier-Stokes (PANS); Large Eddy Simulation (LES) and Computational Fluid Dynamics (CFD)

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